

An Extra Long X-Ray Plateau in a Gamma-Ray Burst and the Spinar Paradigm

V.Lipunov^{1,2,3} & E.Gorbovskoy^{1,2,3}

ABSTRACT

The recently discovered gamma-ray burst GRB 070110 displayed an extraordinary X-ray afterglow with X-ray radiation—i.e., an X-ray plateau—observed for 20,000 s. We show that the observed properties of the plateau can be naturally interpreted in terms of the model with a spinar—a quasi—equilibrium collapsing object whose equilibrium is maintained by the balance of centrifugal and gravitational forces and whose evolution is determined by its magnetic field. If this model is true, then for 1 hr, the Swift X-ray telescopes recorded radiation from an object with a size smaller than the Schwarzschild radius!

Subject headings: Gamma-ray burst, Black holes, magnetic field, rotation

1. Introduction

After three years of the operation of Swift space observatory (Gehrels, N., et al, 2004) it becomes evident that the temporal behavior of many gamma-ray bursts exhibits such features as delayed flares (Chincarini, G., et al., 2007) and early precursors (Lazzati, 2005), which can in no way be reconciled with the instantaneous point explosion model and which are indicative of a long (compared to the duration of the gamma-ray burst) time of operation of the central engine (Gehrels, N., et al, 2006; Wang & Meszaros, 2007).

The recently discovered gamma-ray burst GRB 070110 displayed an extraordinary x-ray afterglow with x-ray radiation — x-ray plateau — observed for 20 000 seconds (Troja, E., et al. 2007). The gamma-ray burst GRB 050904 exhibits a similar behavior (Cusumano et al., 2006). Such a behavior demonstrates the central engine long-activity and gives an insight into the mechanisms of its operation. We show that the observed properties of the

¹Moscow State University

² Sternberg Astronomical Institute

³Moscow Union “Optic”

plateau can be naturally interpreted in terms of a spinar paradigm. The spinar paradigm has a transparent physical meaning, which opens up a way toward successful understanding of GRBs and the accompanying events, and allows their variety to be reduced to two physical parameters – initial angular momentum and initial magnetic field.

2. Spinar Paradigm

The prolonged activity of the central engine of gamma-ray bursts was earlier predicted (Lipunova, (1997); Lipunova & Lipunov, (1998); Vietri & Stella, (1998)) to be a result of the spinar formation. The lifetime of the spinar is determined by the rate of dissipation of its angular momentum as a result of the interaction of the magnetic field of the spinar with the ambient plasma. This is the essence of the spinar paradigm. The origin of the spinar paradigm dates back to 1960-ies when the importance of allowing for magnetorotational effects in the process of collapse has been clearly understood. Spinars were first invoked when analyzing the energy release by and evolution of quasars Hoyle & Fowler (1963); Ozernoy (1966); Ozernoy & Usov, (1973) and ejection of supernovae shells (LeBlanc & Wilson, 1970; Bisnovatyi-Kogan, 1971) .

A spinar may form in two ways: via a collision of two neutron stars (Lipunova & Lipunov, 1998) or via the core collapse of a massive star. Last a situation may arise during late stages of evolution of binary systems where a binary helium star forms with an orbital period of less than one day (Tutukov & Cherepashchuk, 2003). The rate of such events is about $10^{-4} \text{ year}^{-1} \text{ per } 10^{11} M_{\odot}$ (Bogomazov et al., 2007). This rate agrees well with the observed gamma-ray burst rate if we take into account the narrow-beamed nature of the radiation of a gamma-ray burst. Population synthesis of a merging of neutron stars yield a similar rate of $\sim 10^{-4}$ per year per $10^{11} M_{\odot}$ for these events (Lipunov et al., 1987).

Consider now magnetorotational collapse of a stellar core of rest mass M_{core} , radius R_A , and effective Kerr parameter (Thorne et al., 1986) :

$$a_0 \equiv \frac{I\omega_0 c}{GM_{core}^2} > 1, \quad (1)$$

where $I = kM_{core}R_A^2$ — is the moment of inertia of the core; c and G are the speed of light and gravitational constant, respectively, and k is a dimensionless constant, which we set equal to unity for the sake of simplicity. Parameter a remains constant if the angular momentum of the core is conserved (the condition that is evidently violated in our scenario). However, in any case, direct collapse is impossible in such a situation, because the Kerr parameter of a black hole cannot exceed unity. Let α_m be the ratio of the magnetic energy

U_m of the core to its gravitational energy: $\alpha_m \equiv U_m/(GM_{core}^2/R)$. The total magnetic energy can be written in terms of the average magnetic field B that penetrates the spinar, $U_m = (1/6)B^2R^3$. In the approximation of the conservation of magnetic flux ($BR^2 = const$) the ratio of the magnetic and gravitational energies remains constant throughout the collapse: $\alpha_m = const$, $U_m \propto R^{-1}$. The collapse process breaks into several important stages (see Fig.1.). After the loss of stability virtually free-fall contraction begins with a time scale of $t_A = (R_A^3/GM_{core})^{1/2} \sim 100s$, where $R_A \sim 10^{11}cm$ is the initial radius of the stellar core (Wang & Meszaros, 2007 eq. 15). During the collapse the gravitational energy is hardly radiated, but is transformed into kinetic, rotational, and magnetic energy of the core. The rotational energy can be easily seen to grow faster than the gravitational energy $U_{spin} \approx I\omega^2/2 \propto R^{-2}$, and the collapse stops (Fig. 1B) near the radius determined by the balance of the centrifugal and gravitational forces: $\omega^2R_B = GM_{core}/R_B^2$. It follows from this that the initial radius of the spinar is approximately equal to $R_B = a_0^2R_g/2$ (here $R_g = 2GM_{core}/c^2$ is the gravitational radius of the core). In this case, half of the gravitational energy is released: $E_B \approx GM^2/2R_B = (1/2a_0^2)M_{core}c^2$

Because of the axial symmetry the burst must be collimated along the axis of rotation and have an opening angle of Ω_B . If $a_0^2 \leq 100$ the energy of the first explosion exceeds significantly the bounding energy of the stellar shell, and relativistic jet easily comes out. The duration of this stage is determined by the time it takes the jet to reach the surface and by the nature of cooling, which in turn is determined by the structure of the initial jet and the shell, and ranges from several seconds to several hundred seconds. The nature of the spectrum is determined by the Lorentz factor of the jet (Wang & Meszaros, 2007). The spinar that forms it the core interiors begins to lose its angular momentum due to magnetic viscosity and starts to radiate its rotational energy. The angular velocity of the spinar increases like that of a satellite whose velocity increases as it decelerates in the upper layers of the atmosphere. The spinar contracts as its angular momentum is carried away under the influence of the maximum possible magnetic torque (Lipunov, 1992):

$$dI\omega/dt \approx - \int_R^\infty \frac{B^2}{4\pi} r 2\pi r dr \approx -U_m. \quad (2)$$

The time scale of the dissipation of angular momentum is $t_C \approx I\omega/U_m = GM_{core}/c^3\alpha_m$. During this process, the velocity of rotation of the spinar increases and the spinar luminosity not only does not decrease, but even increases $L = -\omega dI\omega/dt = U_m\omega \propto R^{-5/2}$. If computed without the allowance for relativistic effects, the spinar light curve has the form:

$$L = \frac{\alpha_m c^5}{a_0^5 G} (1 - t/t_C)^{-3/5} \quad (3)$$

The luminosity remains virtually constant and equal to $L_{plato} = \frac{\alpha_m}{a_0^5} \frac{c^5}{G}$ while $t \ll tc!$ Thus even in the Newtonian approximation the spinar model predicts a plateau whose parameters can be estimated from the latter two formulas. If the magnetic field is sufficiently strong and t_C is small, the spinar produces an X-ray flare.

General relativity effects begin to show up as the spinar radius approaches the gravitational radius. In particular, the magnetic field of the collapsar begins to vanish in full agreement with the black-hole-no-hair theorem (Thorne et al., 1986). The general-relativity evolution for the magnetic field of the collapsar has been computed repeatedly by several researchers (Ginzburg & Ozernoy, 1964; Kramer, 1984; Manko & Sibgatullin, 1992). The results of Ginzburg & Ozernoy (1964) computations can be approximately modified. As next formula correctly describes the behavior of magnetic energy at large distances from the gravitational radius and yields zero magnetic field at the event horizon:

$$U_m = U_0 \frac{x_0}{x} \frac{\xi(x_0)}{\xi(x)} \quad (4)$$

where $\xi(x) = \frac{1}{x} + \frac{1}{2x^2} + \ln(1 - 1/x)$, $x = R/2R_g$.

The second important group of effects consists in the reference-frame drag in the metric of the rotating body and in relativistic effects due to the close location of the event horizon. We use the post-Newtonian approximation for the centrifugal force in the Kerr metric to allow for the latter two effects (Mukhopadhyay, 2002):

$$g = \frac{GM(x^2 - 2ax^{1/2} + a^2)^2}{x^3(x^{1/2}(x - 2) + a^2)^2}, \quad x = R/2R_g. \quad (5)$$

The curve of energy release acquires the features of a burst, which can be approximately described by the following set of elementary equations:

$$\begin{aligned} \omega^2 R &= g, dI\omega/dt = -U_m \\ L_\infty &= \alpha^2 L_C = \alpha^2 U_m \omega, dt_\infty = dt/\alpha \end{aligned} \quad (6)$$

Here L_∞ and t_∞ are the luminosity and time in the reference frame of an infinitely distant observer and α is the duration function – the ratio of the rate of the clock of reference observers to the universal time rate at the equator of the Kerr metric (Thorne et al., 1986):

$$\alpha = \sqrt{\frac{x^2 + a^2 - 2x}{x^2 + a^2}}, \quad (7)$$

which vanishes ($\alpha \rightarrow 0$) at the horizon of the extremely rotating black hole $R \rightarrow R_g/2$.

As the luminosity increases, the condition of shell penetration becomes satisfied at a certain time instant. A second jet appears whose intensity reaches its maximum near the gravitational radius. In this case, the effective Kerr parameter tends to its limiting value for a Kerr black hole $a \rightarrow 1$. The subsequent fate of the star depends on its mass. If the mass exceeds the Oppenheimer—Volkoff limit the star collapses into a black hole. Otherwise a neutron star forms, which continues to radiate in accordance with the magnetodipole formula $L \propto t^{-2}$ (see for example Lipunov, 1992).

The spinar paradigm allows the observed variety of gamma-ray bursts, precursors, and flares to be reduced to just two parameters: magnetic field and initial angular momentum (Fig.2).

3. X-ray plateau explanation

What is a plateau in the spinar paradigm? The simple answer is: an extralong X-ray plateau is an x-ray flare protracted for several thousand seconds because of the weak magnetic field of the spinar. Figure 3 shows the rest-frame light curve of the gamma-ray bursts GRB 070110 and GRB 050904 adopted from (Troja, E., et al., 2007). Both bursts had large redshifts ($z = 2.5$ and $z = 6.6$) and therefore the observer sees the duration of the corresponding plateaux to be three-seven times longer than their rest-frame durations. Both bursts exhibited extralong plateaux which ended abruptly at the 8000th second. Note that the energy was computed in isotropic approximation. We therefore did not strive to achieve the exact coincidence of luminosities, especially because we do not know the factor of conversion of the released energy into the x-ray flux. Moreover, we have no information about the detailed structure of the beam pattern and therefore both bursts can be explained in terms of the same model provided that we see them at different angles. However, the most important factor is the duration of the plateau.

Figures 3b-e show the exact solution of the set of equations (6), which agrees excellently with the observed plateau events for GRB 070110 and GRB 050904. Both plateaux can be best described in terms of the model of the collapse of a $7M_{\odot}$ star with the initial rotation energy fraction of $\alpha_m = 1.0 \times 10^{-7}$ and initial Kerr parameter $a = 2.0$. With these parameter values the above scenario should appear as follows. The loss of stability by the rapidly rotating star results in the formation of a spinar and release of energy $E_B \approx (1/2a^2)M_{core}c^2 \approx 4.5 \times 10^{53} \text{ erg}$. The complex process of the emergence of a high-Lorentz-factor relativistic jet onto the surface produces an about 100-s long gamma-ray burst. After the jet comes out to the surface an afterglow ($\sim t^{-2}$) appears due to the curvature effect (Kumar & Panaitescu, 2000). Then, after the 300th second, most of the energy is radiated by the bow

shock, which is decelerated in the stellar wind of the progenitor star (t^{-1}) (Troja, E., et al., 2007). During this process the spinar continues to radiate at a virtually constant luminosity, which shows up at the 1000th second, when the afterglow faded significantly. The luminosity remains virtually constant afterward. After a small increase of the luminosity due to the compression of the spinar the plateau terminates with the luminosity dropping abruptly, the spinar radius becomes smaller than the gravitational radius, and the spinar is now located inside the ergosphere of the future black hole! The abrupt increase of the gravitational redshift and effects of the disappearance of magnetic field result in the abrupt decrease of the spinar luminosity, which continues to fall for about 900 seconds until the intensity becomes lower than the luminosity of the bow shock. During all this time the spinar is inside the ergosphere, $R_g/2 < R < R_g$. It seems that mankind has never before come so close to the event horizon! Since real gamma-ray bursts are located at large redshifts, the time intervals measured with our Earth clocks are a factor of $(1 + z)$ longer than the corresponding rest-frame time intervals, providing us with an opportunity to study the collapse inside the ergosphere for up to 2500 – 9000s, i.e., virtually during an entire hour! Figure 3b shows the synthetic light curve computed with the allowance for the afterglow, $L = C_1 t^{-2} + C_2 t^{-1} + L_\infty$, which agrees well with the observed light curve. The small flare at 5000 – 10000s after the period of steep decay in GRB070110 is the result of energy input from spinar to bow shock. After end of the plateau the level of the afterglow emission must change, but with some delay.

The model of a magnetized spinar demonstrates how the parameters of the observed plateau depend on the physical parameters of the progenitor. Our model naturally explains other, fainter events in all types of gamma-ray bursts, which we discuss in a separate paper.

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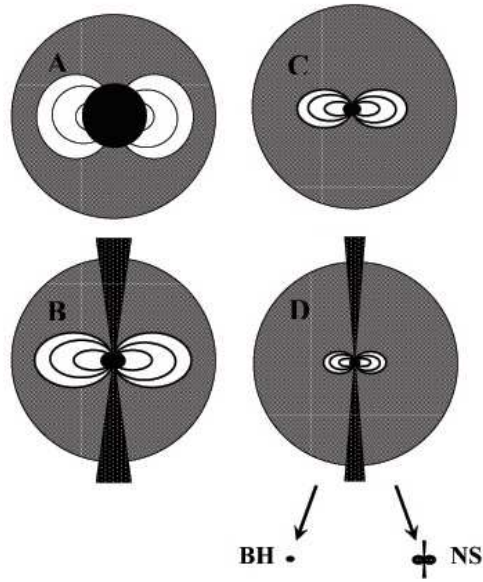


Fig. 1.— Schematic view of the collapse of the rapidly rotating magnetized core of a massive star. Gray and black shaded areas show the envelope and core of the star, respectively.

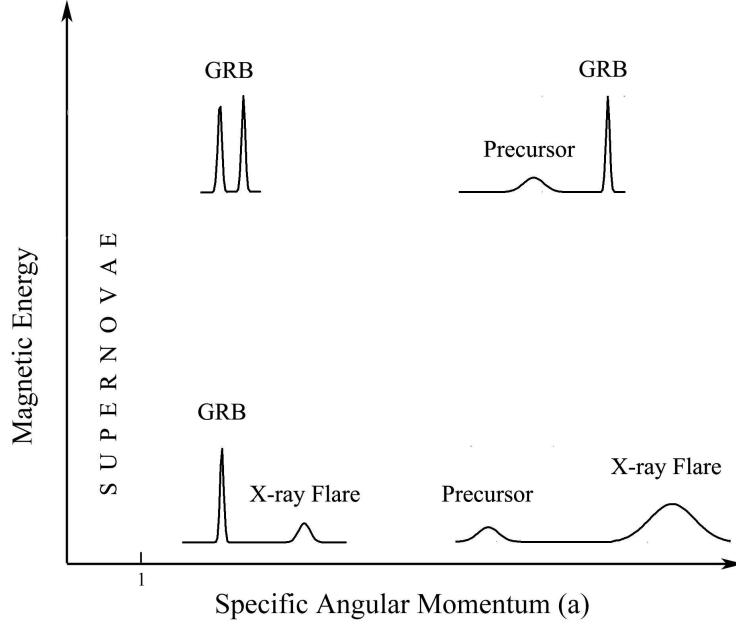


Fig. 2.— Classification of GRBs and surrounding events in terms of the spinar paradigm. In the case of weak magnetic field and large angular momentum (the bottom right curve) the first burst is weak (because of the high centrifugal barrier) and soft. It is followed by slow collapse (magnetic field is weak), which results in a weak x-ray burst. In the case of small angular momentum (the bottom left curve) the energy released at the centrifugal barrier is large and the burst appears as a gamma-ray burst, whereas the second burst, which corresponds to the collapse of the spinar, is again weak and soft and shows up as a distant x-ray burst. In the case of even weaker magnetic field the second flare behaves as an extralong X-ray plateau. In the case of stronger magnetic field the flare becomes more like a gamma-ray burst, its energy increases and the flare itself becomes part of a gamma-ray burst (the top left curve). As we move rightward, the angular momentum increases and the first flare loses its energy to become a close precursor of the second flare, which in the case of a strong magnetic field becomes a powerful gamma-ray burst. The collapse of a core with the effective Kerr parameter smaller than unity results in a supernova explosion.

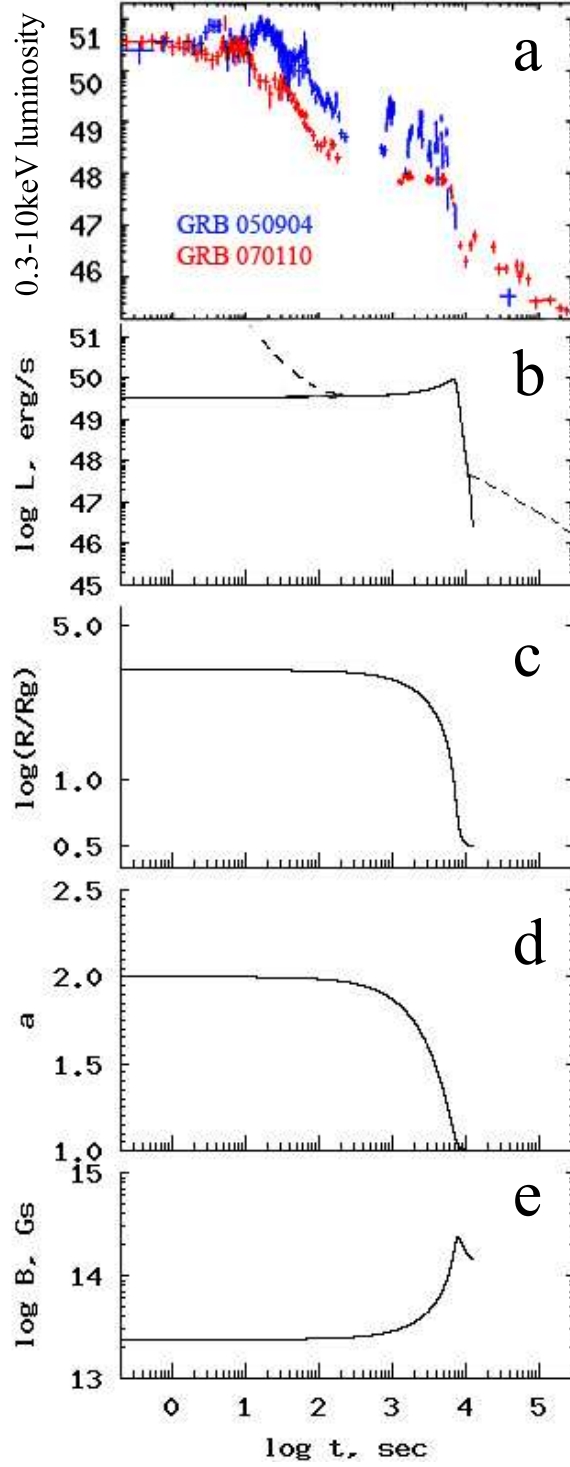


Fig. 3.— Figure 3a Combined Swift (BAT and XRT) light curves of GRB 050904 ($z=6.29$) and GRB 070110 ($z=2.35$) in the source rest frame (Troja, E., et al 2007) Figures 3b-c show the result of the computation of the spinar luminosity, radius and effective Kerr parameter, respectively. The mean magnetic field evolution (Figure 3e) is calculated under the approximated general relativistic model (see eq. 4)